Scaling properties of hadron production in Au+Au and d+Au collisions at RHIC

(The search for partonic degrees of freedom)

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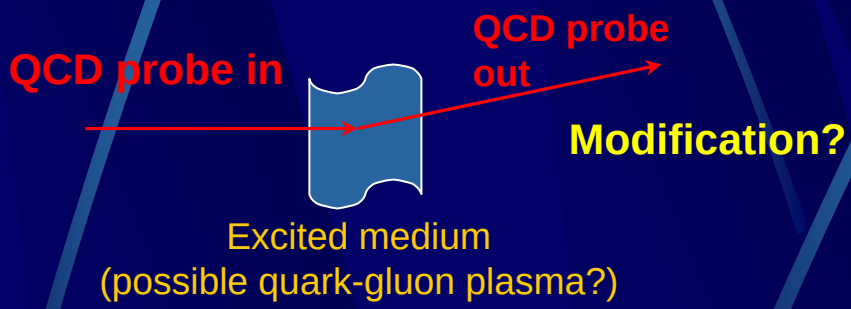
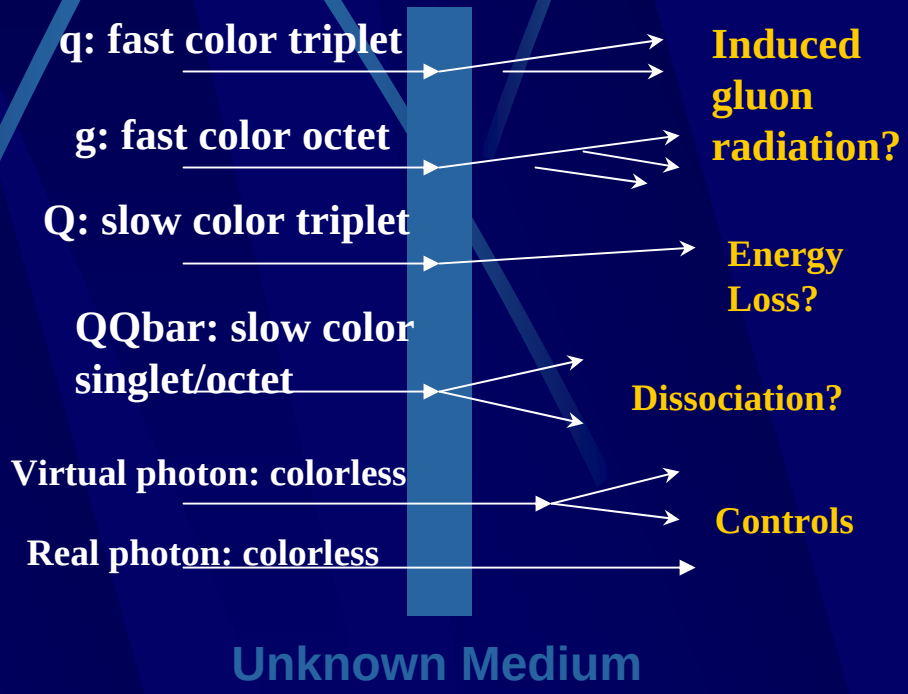
High-Energy Heavy-Ion Physics (in Brief)

A **main goal** of relativistic heavy ion physics is to investigate **high-temperature, high-density QCD**, by creating and then studying the **highly-excited medium** produced in high-energy nuclear collisions.



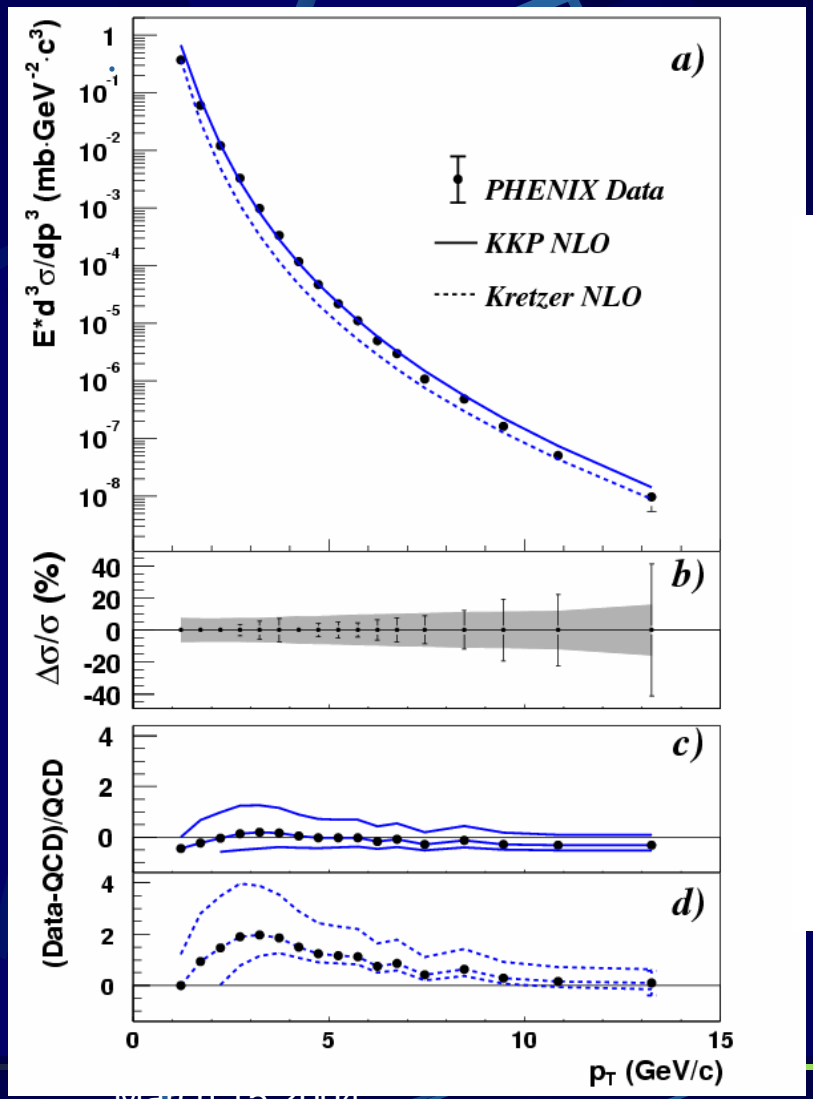
One method of diagnosing a QCD medium is to shoot a QCD-sensitive probe through it, then look for any modifications due to the medium. (Most obvious possibilities: multiple scatterings, induced radiations, and energy loss.)

The full pallet of QCD probes can be created and measured in the PHENIX experiment



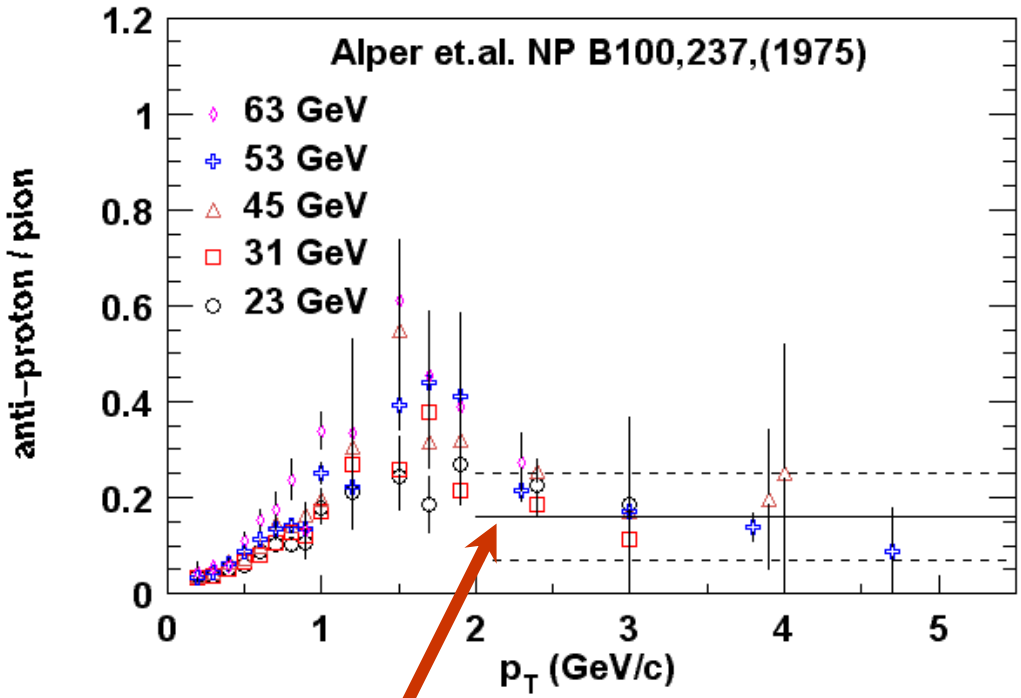
pQCD description in pp

Phys. Rev. Lett. 91, 241803 (2003)



pQCD calculations work

Note: fragmentation function input from experiment



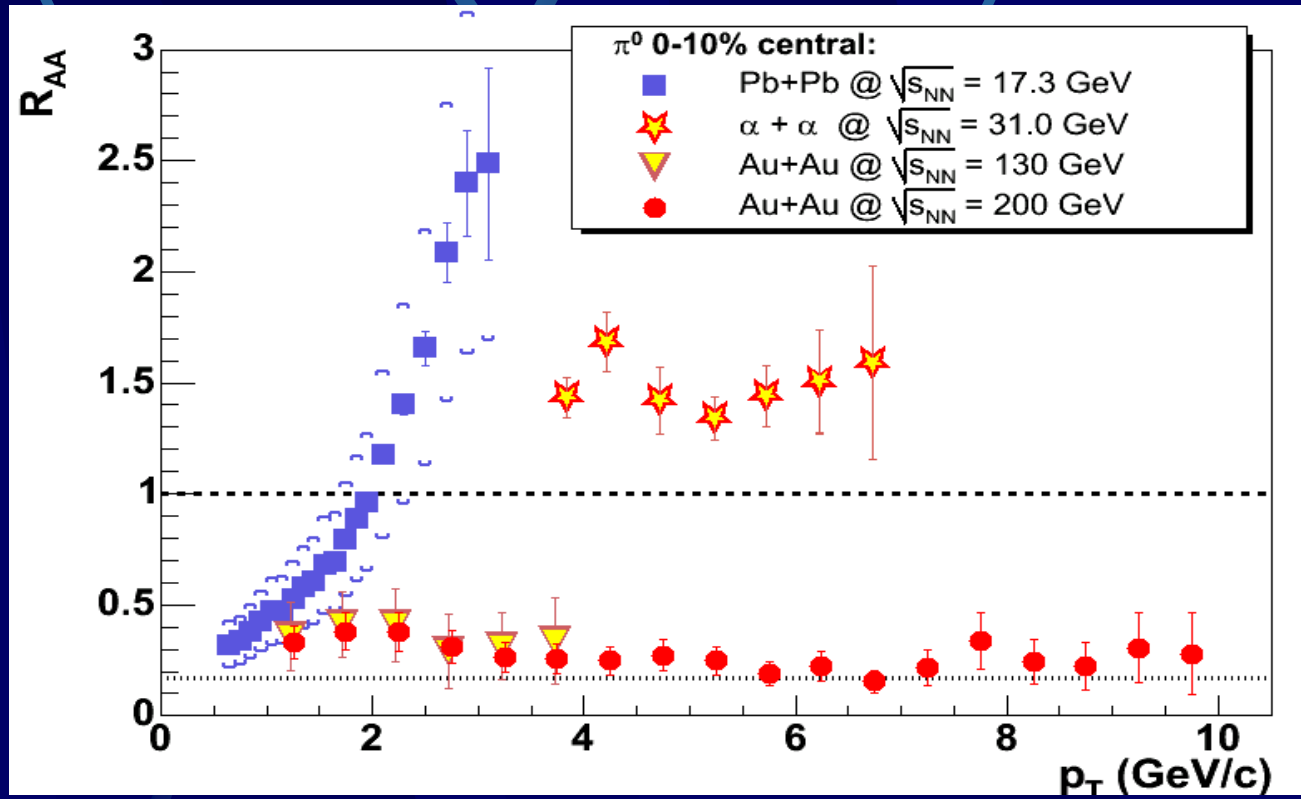
Soft to hard transition in p/π ratio

Nuclear modifications to hard scattering

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

Large Cronin effect at SPS and ISR

Suppression at RHIC



Is the suppression due to the medium? (initial or final state effect?)

The null result on the cover of PRL: dAu

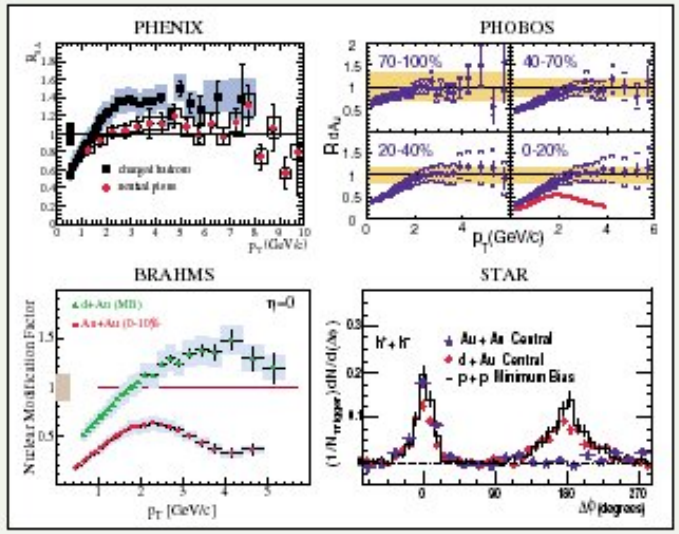
The suppression of hadrons at mid-rapidity is due to the medium produced in the collisions.

(final state)

PHYSICAL REVIEW LETTERS

Articles published week ending
15 AUGUST 2003

Volume 91, Number 7

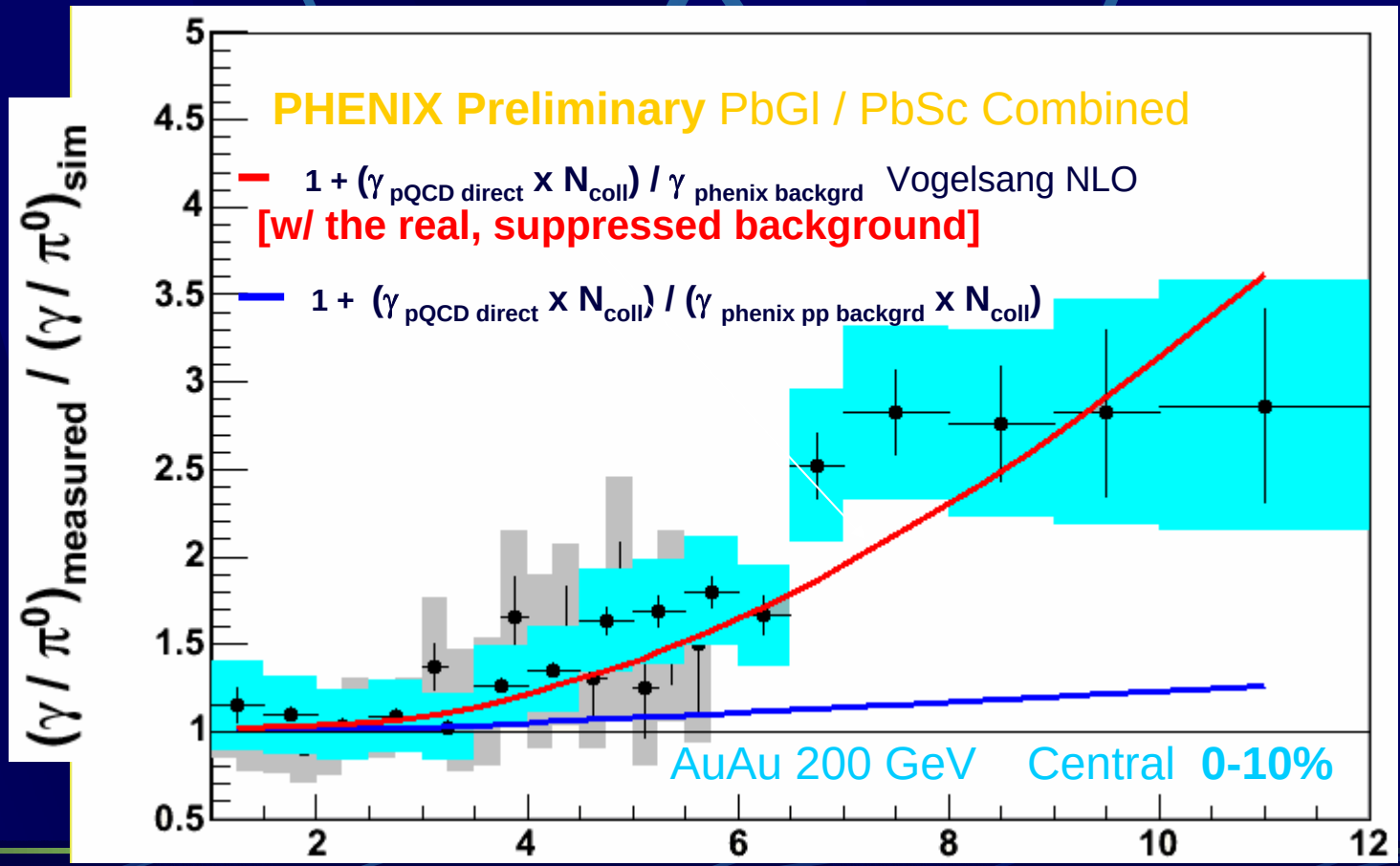


APS Published by The American Physical Society

Direct photons: a colorless probe

Built-in control experiment in the AuAu data.

Direct photons are described by a curve that includes the measured suppressed π^0 production in AuAu.

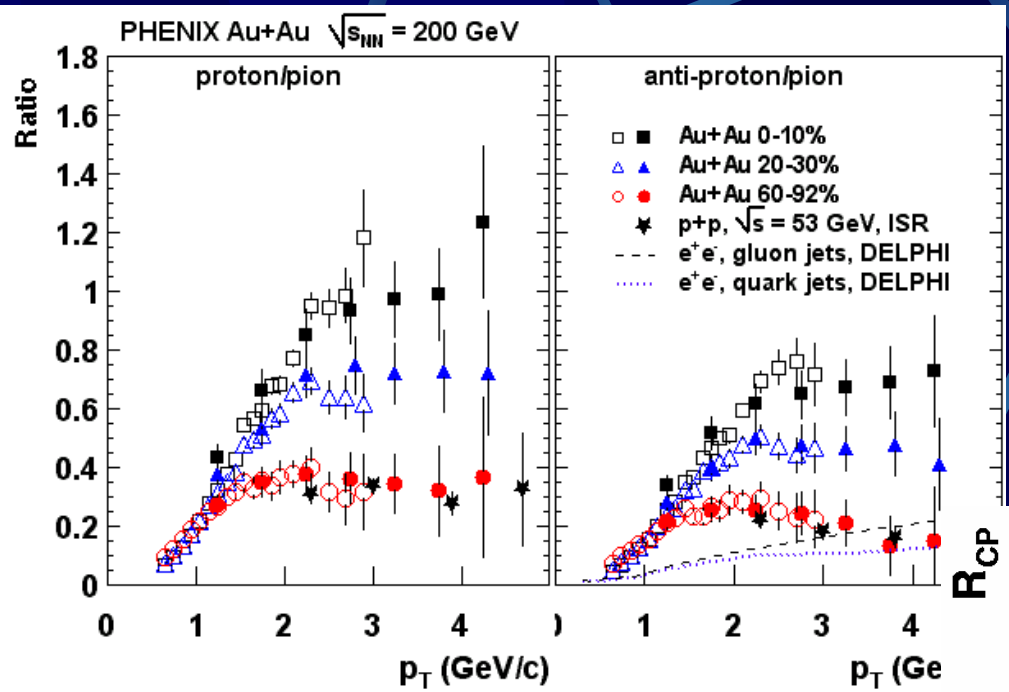


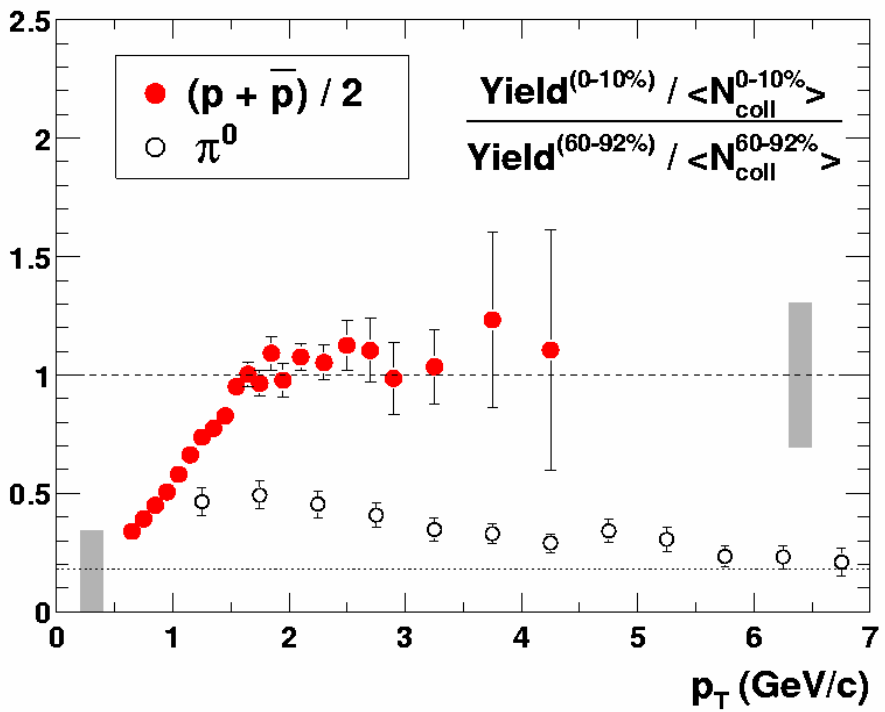
But (anti)protons are not so well behaved

Phys. Rev. Lett 91, 172301 (2003).

Peripheral: consistent with standard fragmentation

Central: a factor ~ 3 higher than peripheral, e^+e^- and ISR pp data



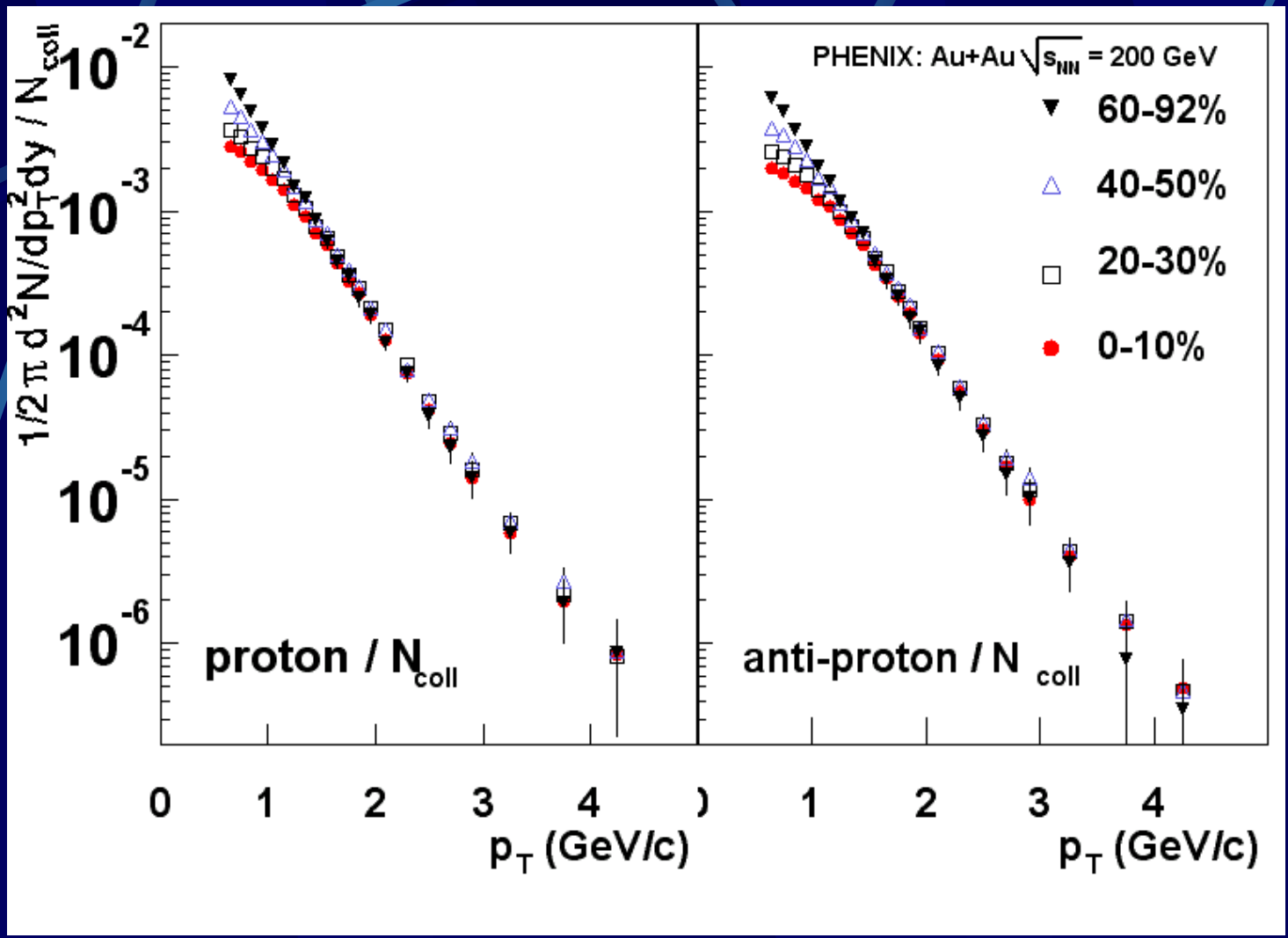


Pions are suppressed at high pT in central Au+Au collisions

No apparent proton suppression for 2-4 GeV/c

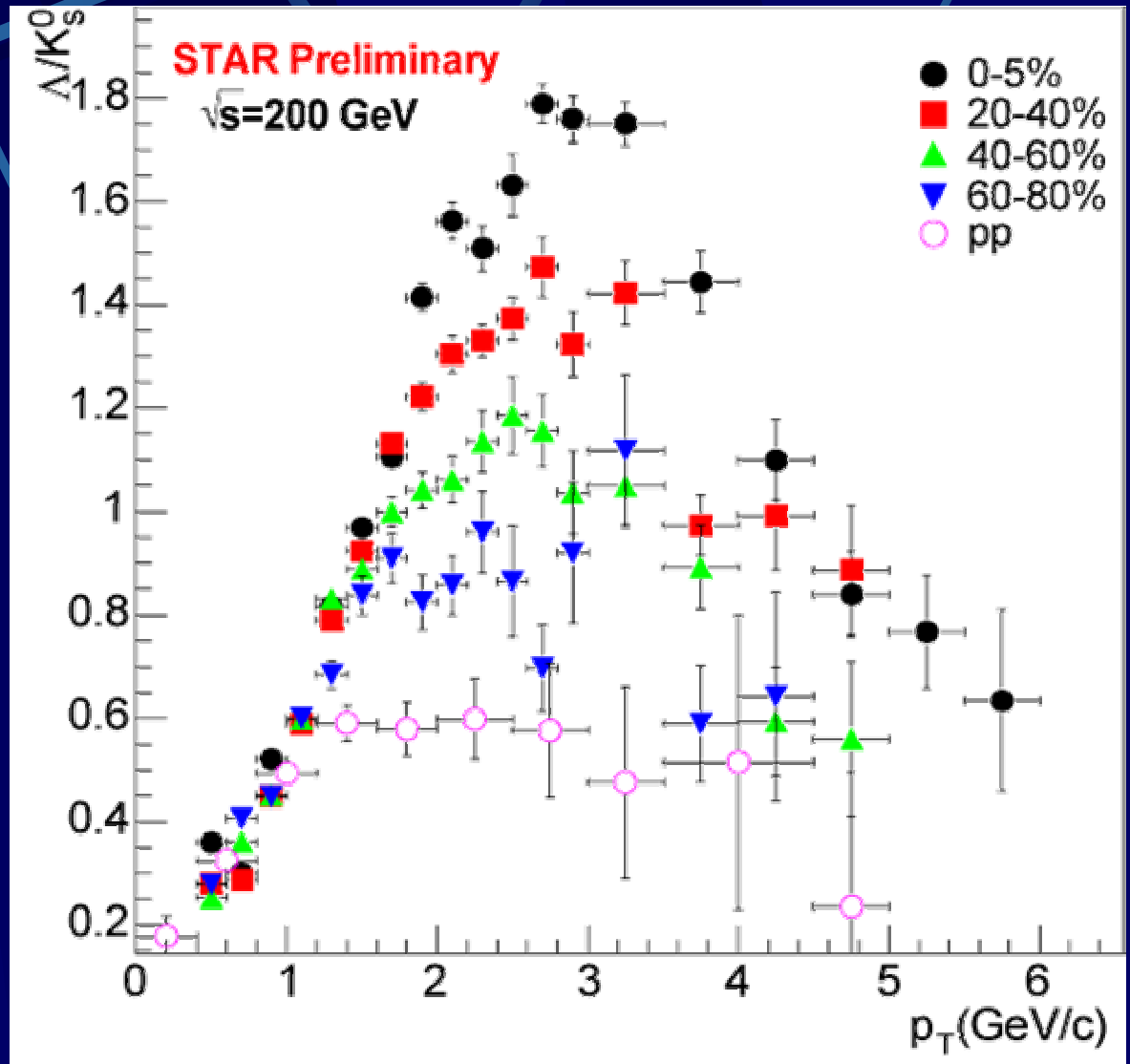
different production mechanism ?

For protons: all centralities scale, while pion suppression increases with centrality

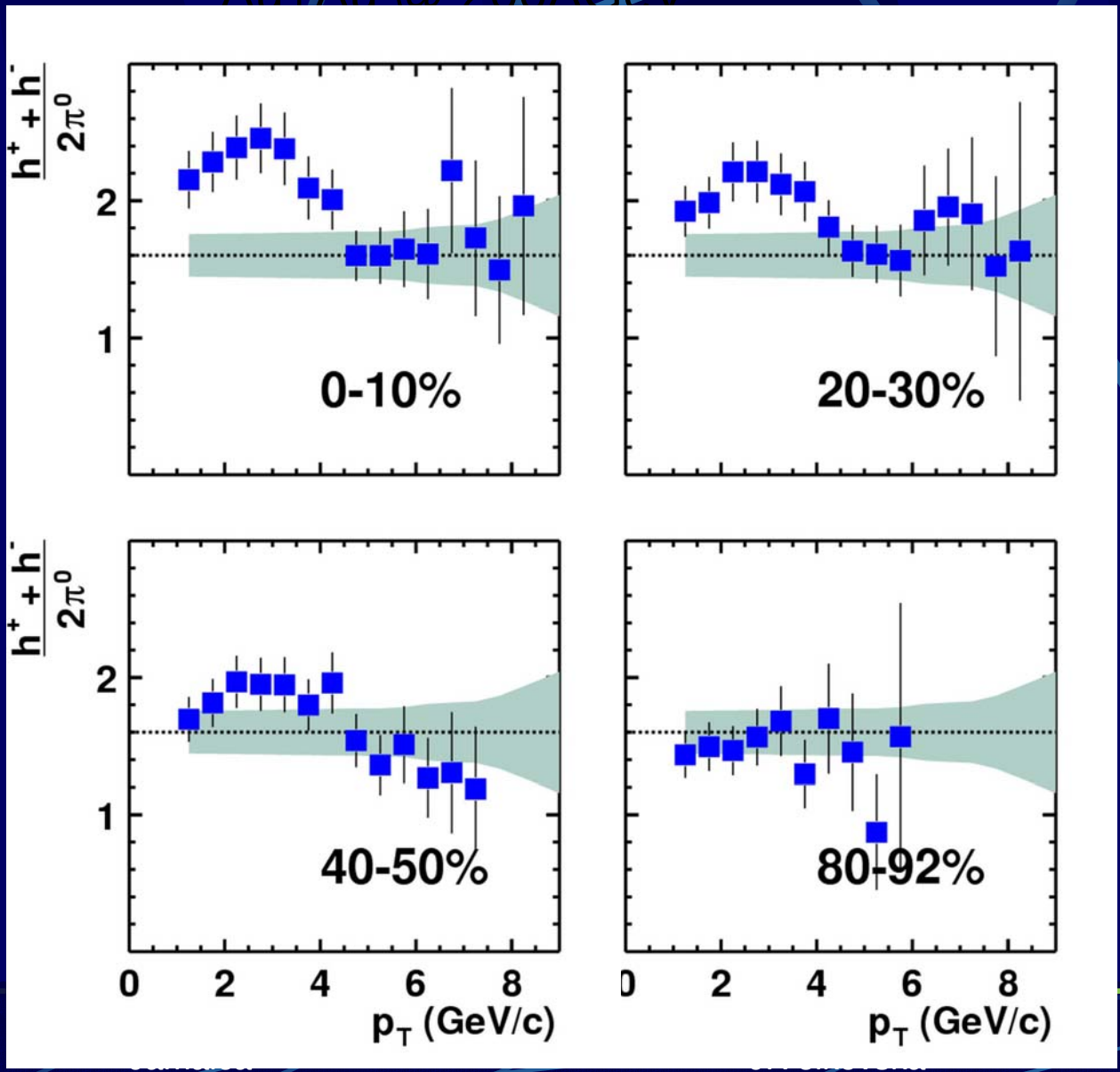


Strange baryon/meson ratios

- The mid-pT anomaly not unique to p/π: also seen for strange particles
- With a little higher p_T reach: Λ/K^0_s has a peak at ~ 3GeV/c
- Height depends on centrality
- Peripheral – above pp data



The proton "bump" in the h/π ratios



Expectation (pp, e^+e^-): $h/\pi \approx 1.6$

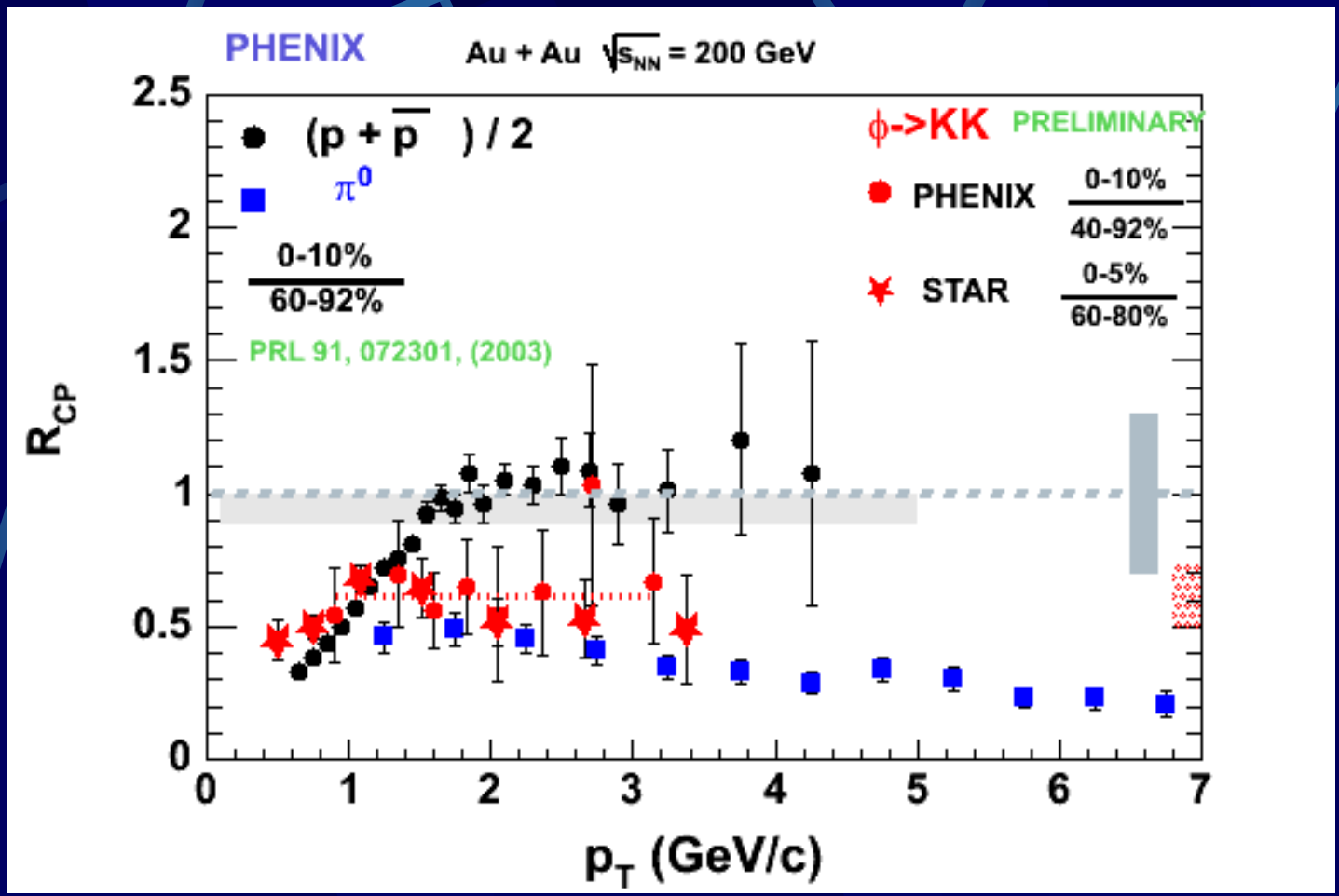
Above 5 GeV/c and in peripheral collisions:

- **recover standard fragmentation**

What is the baryon production mechanism in the "bump"?

- Soft (described by hydro):
  - Mass rather than baryon effect. Questionable applicability out to 4 GeV/c. Can be tested by measuring heavy mesons
- Hard
  - Needs in-medium modification of the fragmentation function
  - Or something exotic, like a colorless baryon junction participating in hard scattering
- Recombination of quarks:
  - Thermal only
  - Thermal + shower(hard)
- Cronin effect (larger for protons)

A meson heavier than the proton can solve the mystery: ϕ scaling

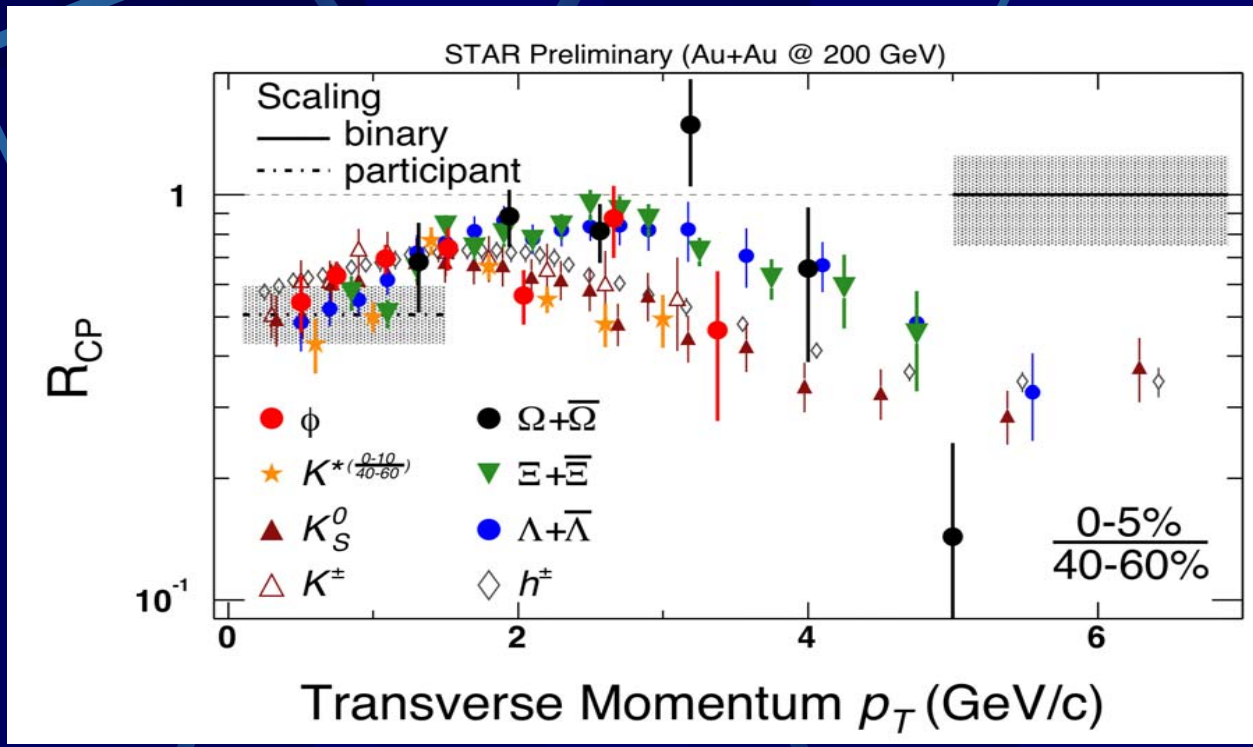


- Meson/baryon , not mass effect!

But what if ϕ decouples early from the fireball ?

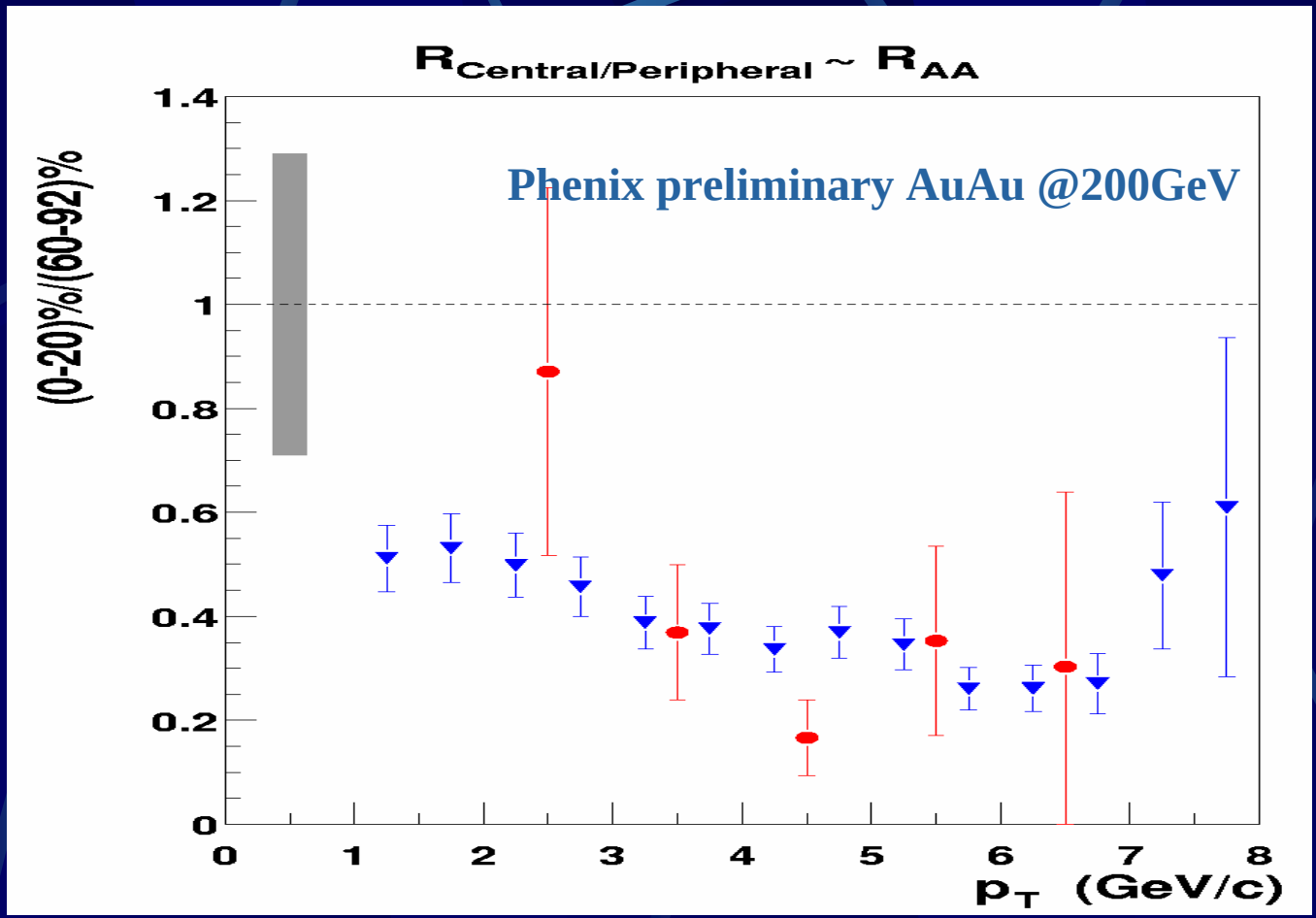
The same should be true for Ω and Ξ, but they are up with the other baryons.

K* joins the mesons.



With PHENIX and STAR data taken together, the baryon/meson distinction is established. Clearly, we have an observable in which the number of quarks in the hadrons is important!

The η meson: high-pt comparison with π^0

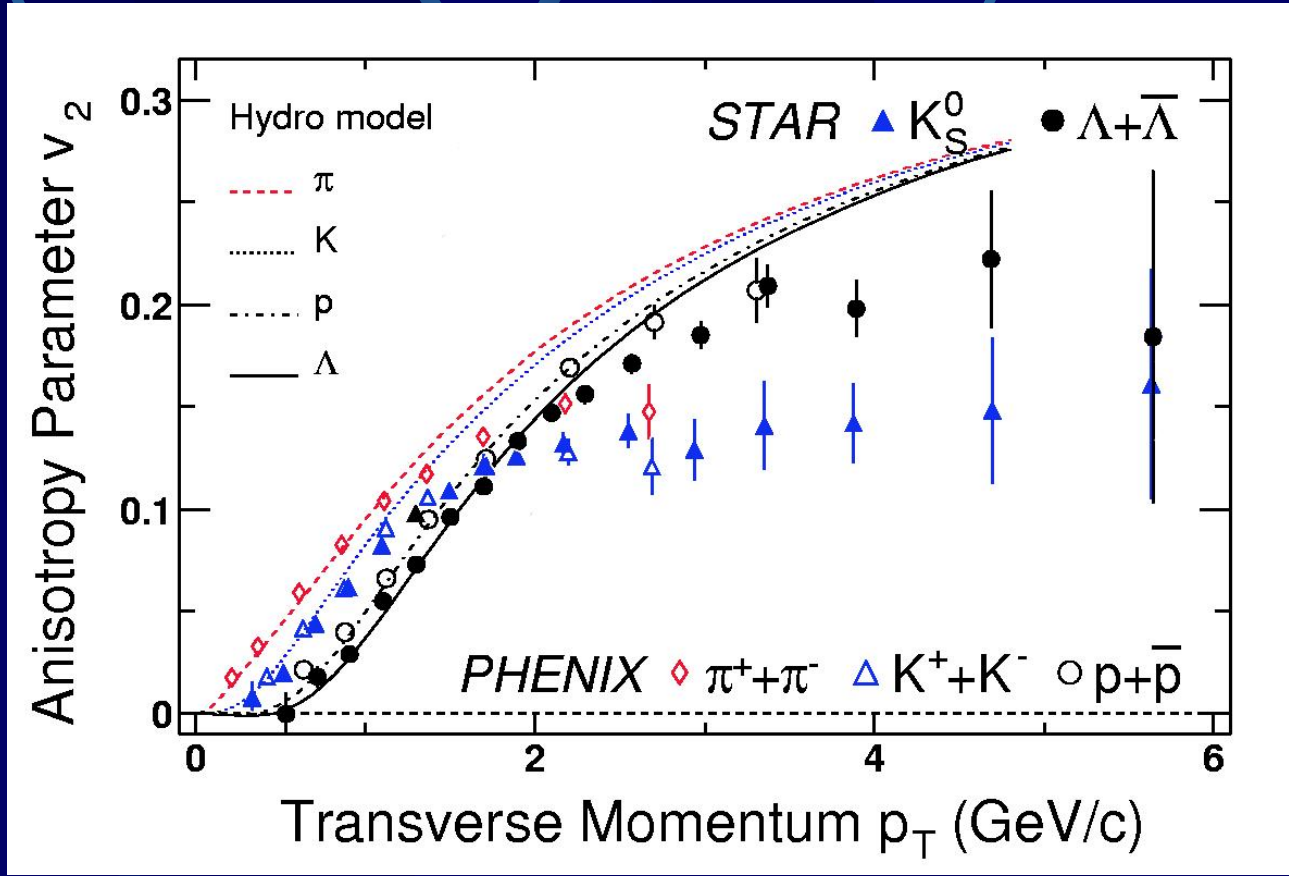


- Adding η into the mix: agrees with π^0 within errors
- There are no exceptions to the baryon/meson distinction in the data currently available

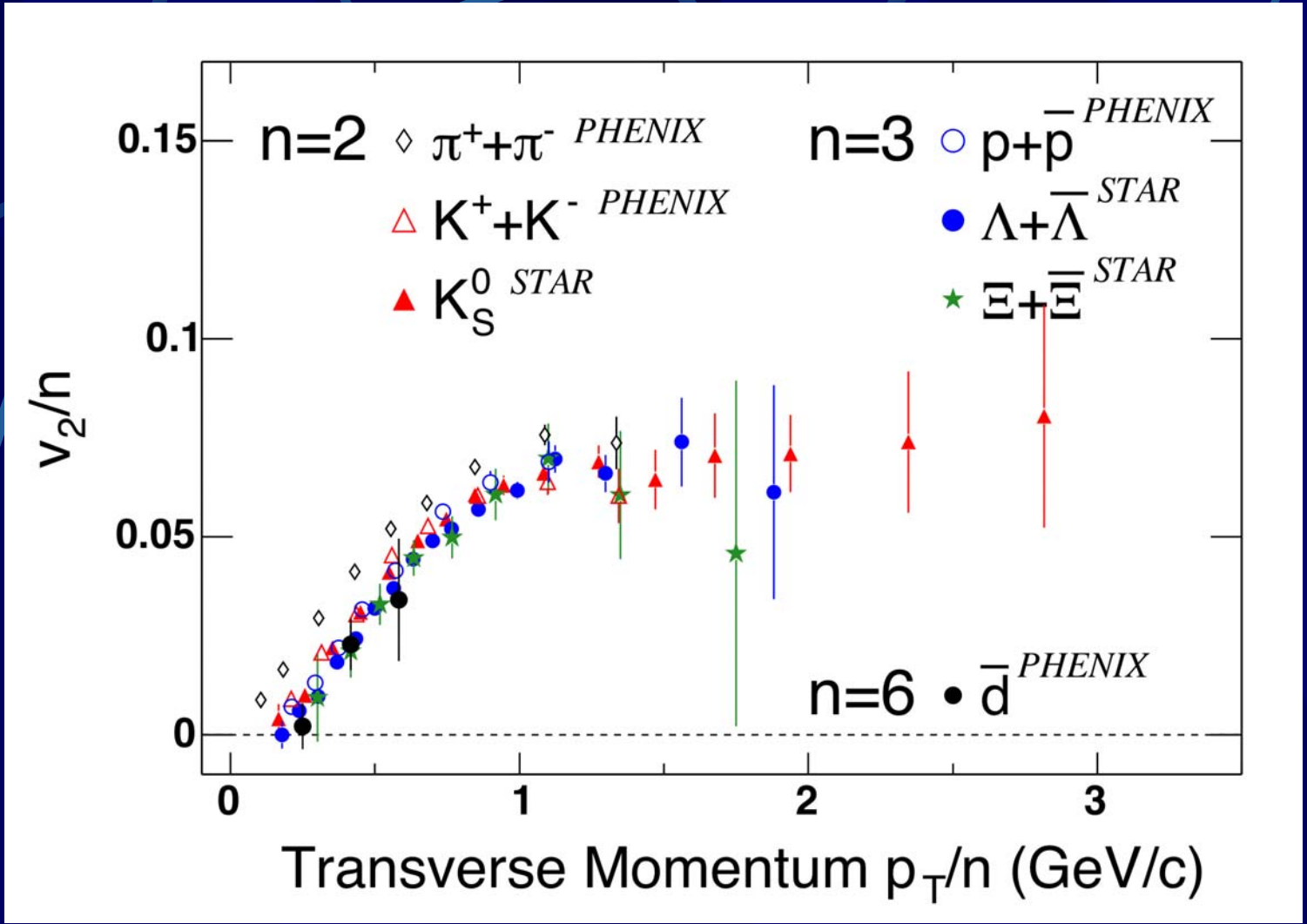
Elliptic Flow strengthens the case for partonic degrees of freedom even further

At low p_T hydro works remarkably well

Above ~ 2 GeV/c :
A split between mesons and baryons

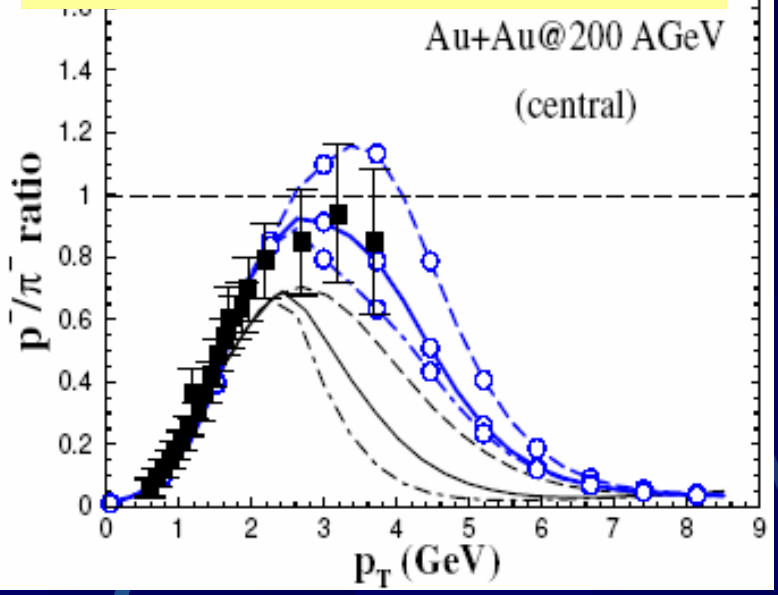


Universal behavior in flow per quark



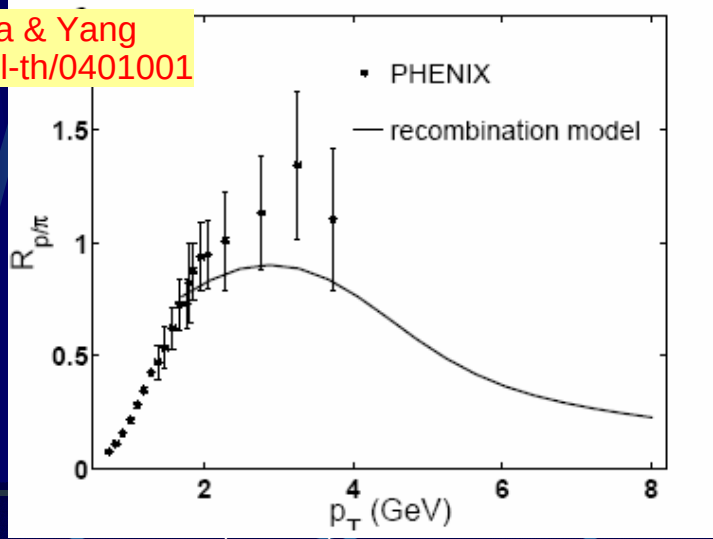
Coalescence/recombination models

Greco, Ko, Levai: Phys.Rev.Lett. 90 (2003) 202302

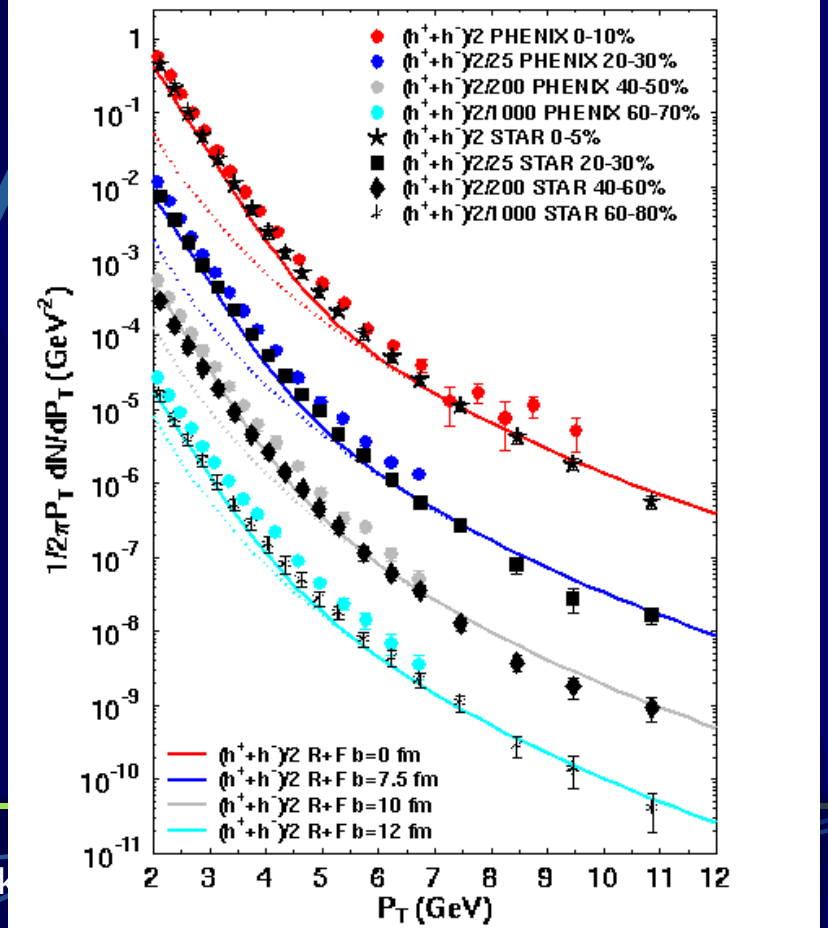


- describe particle ratios , spectra, v2:
- **p_T(baryons) >p_T(mesons)>p_T(quarks)**

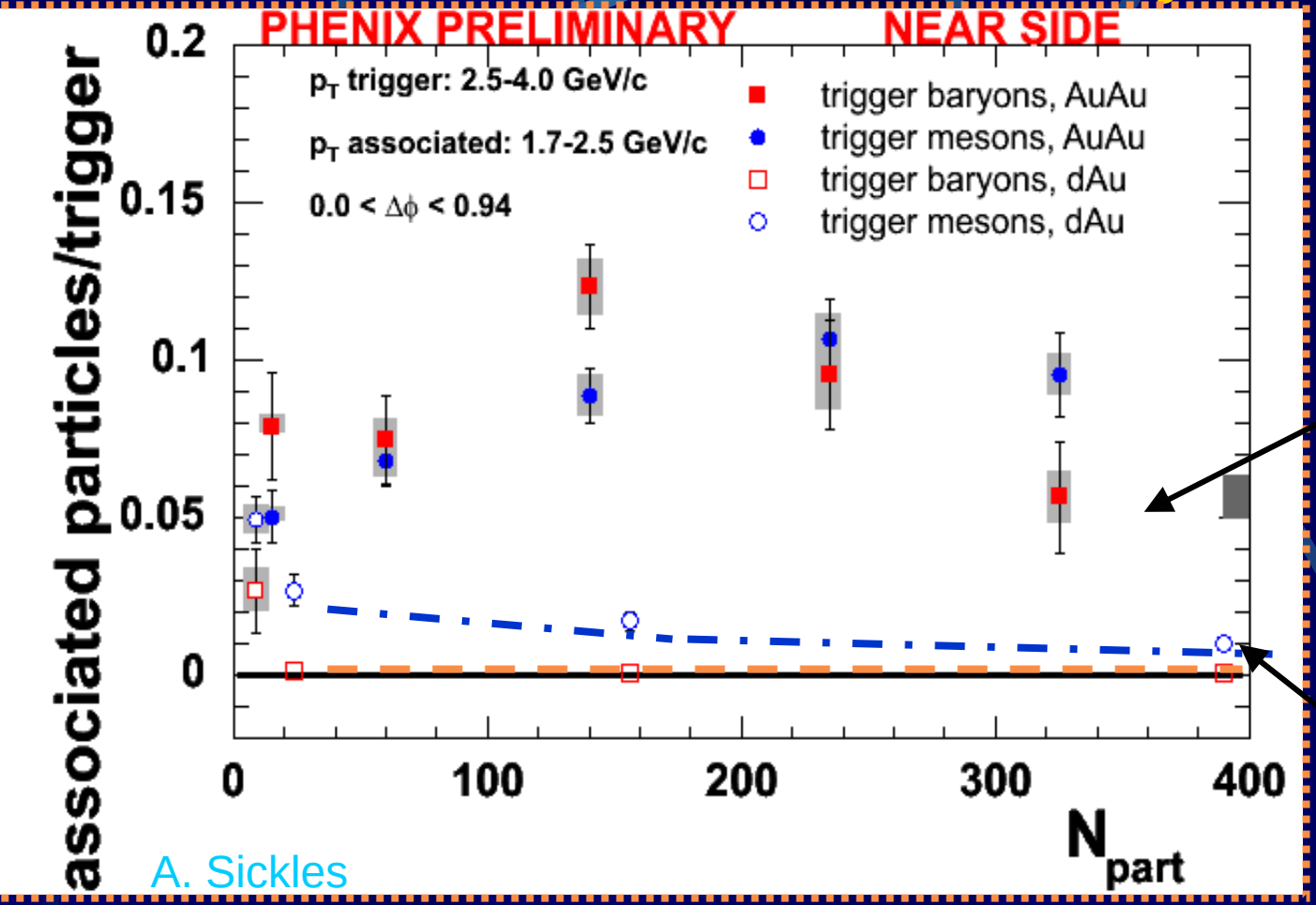
Hwa & Yang nucl-th/0401001



Fries et al: Phys.Rev. C68 (2003) 044902



Jet correlations with identified mesons and baryons

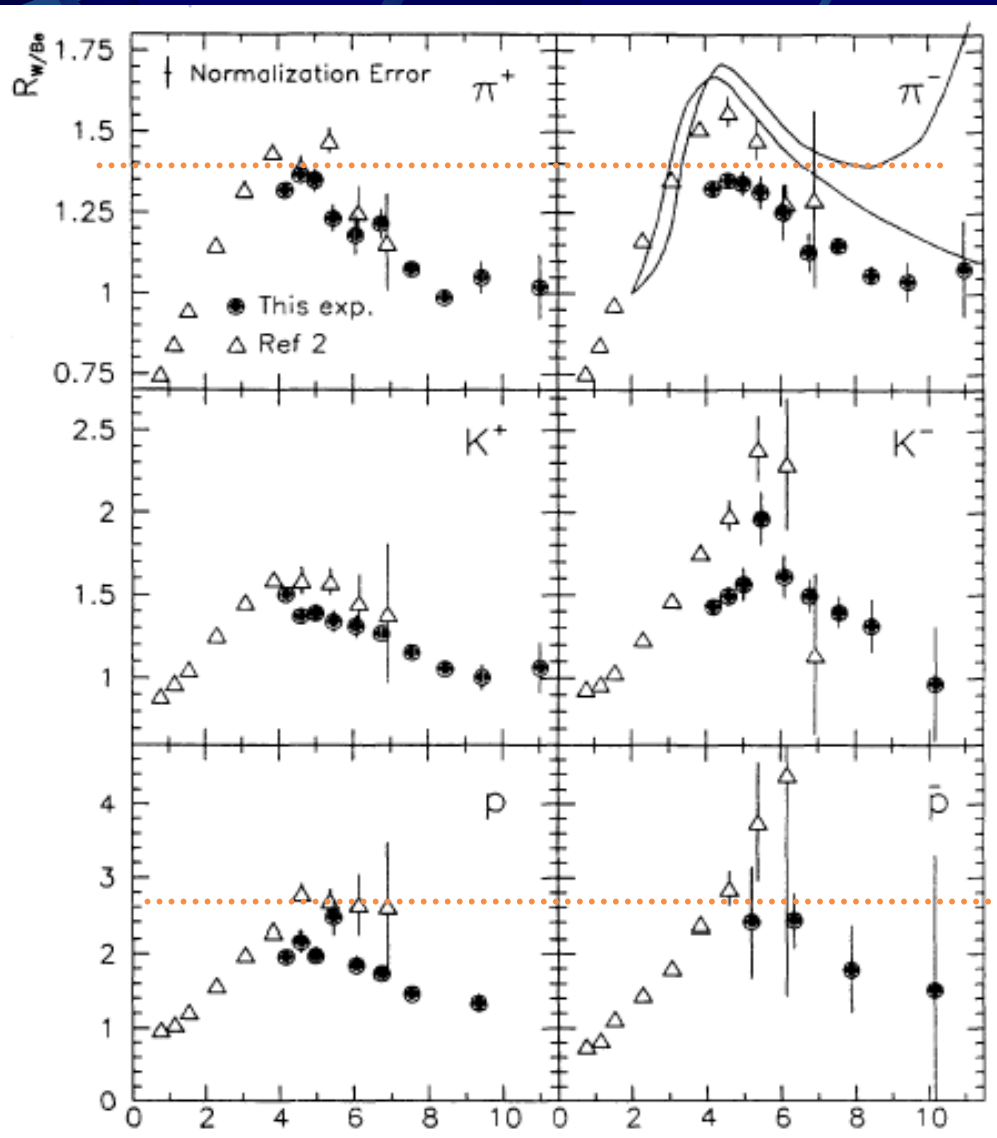


- **jet partner equally likely for trigger baryons & mesons**
- **slight decrease of baryon associated particles with centrality!**
- **expected from purely thermal recombination (nucl-th/0306027)**

Shower-thermal recombination still works.

But what about the Cronin effect ?

- Can Cronin effect produce the enhanced p/π ratio in AuAu ?
- What is Cronin effect? The status at the time of QM2004: Theorists seem to agree:
  - "Initial state multiple scattering leading to pt broadening."
- Why is it different for protons and pions ?
  - "Nobody really knows."



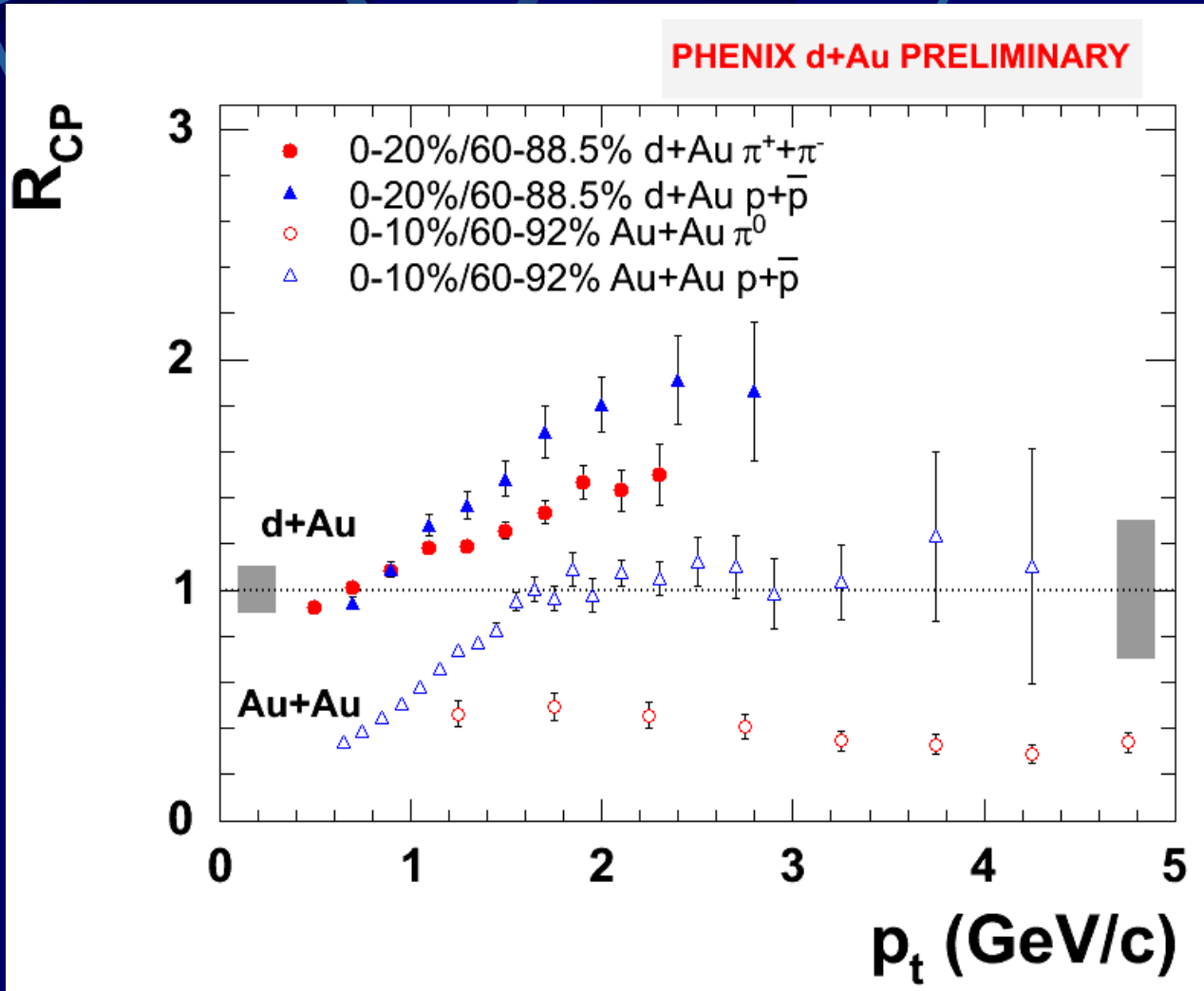
P.B. Straub et al., PRL 68 (1992)
FNAL experiments measuring R (W / Be)
for identified particles at sqrt(s) of 27.4 and 51.3 GeV.

Cronin effect stronger for protons than for pions

- Not enough to account for

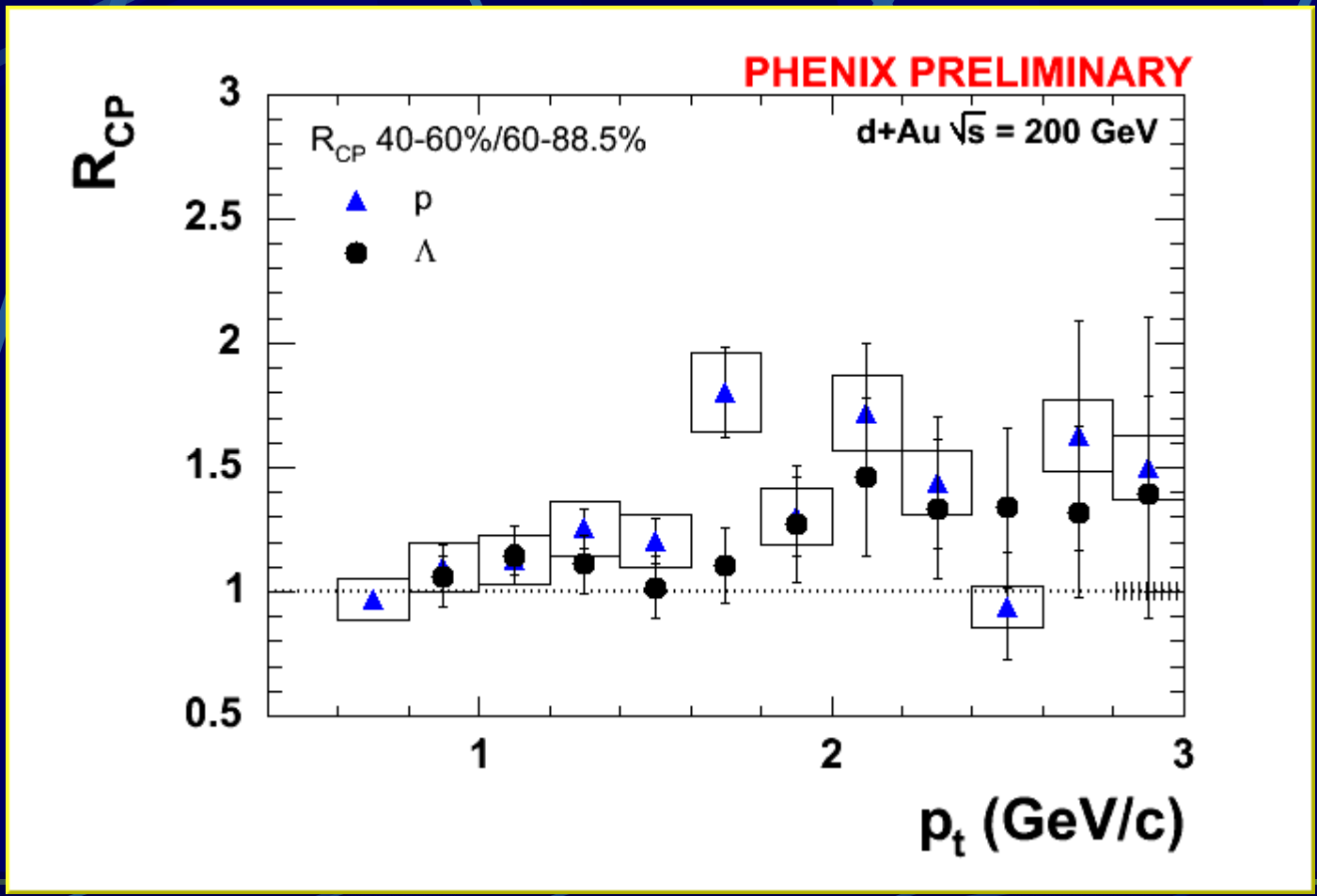
factor of 3 increase

of p/π in central AuAu



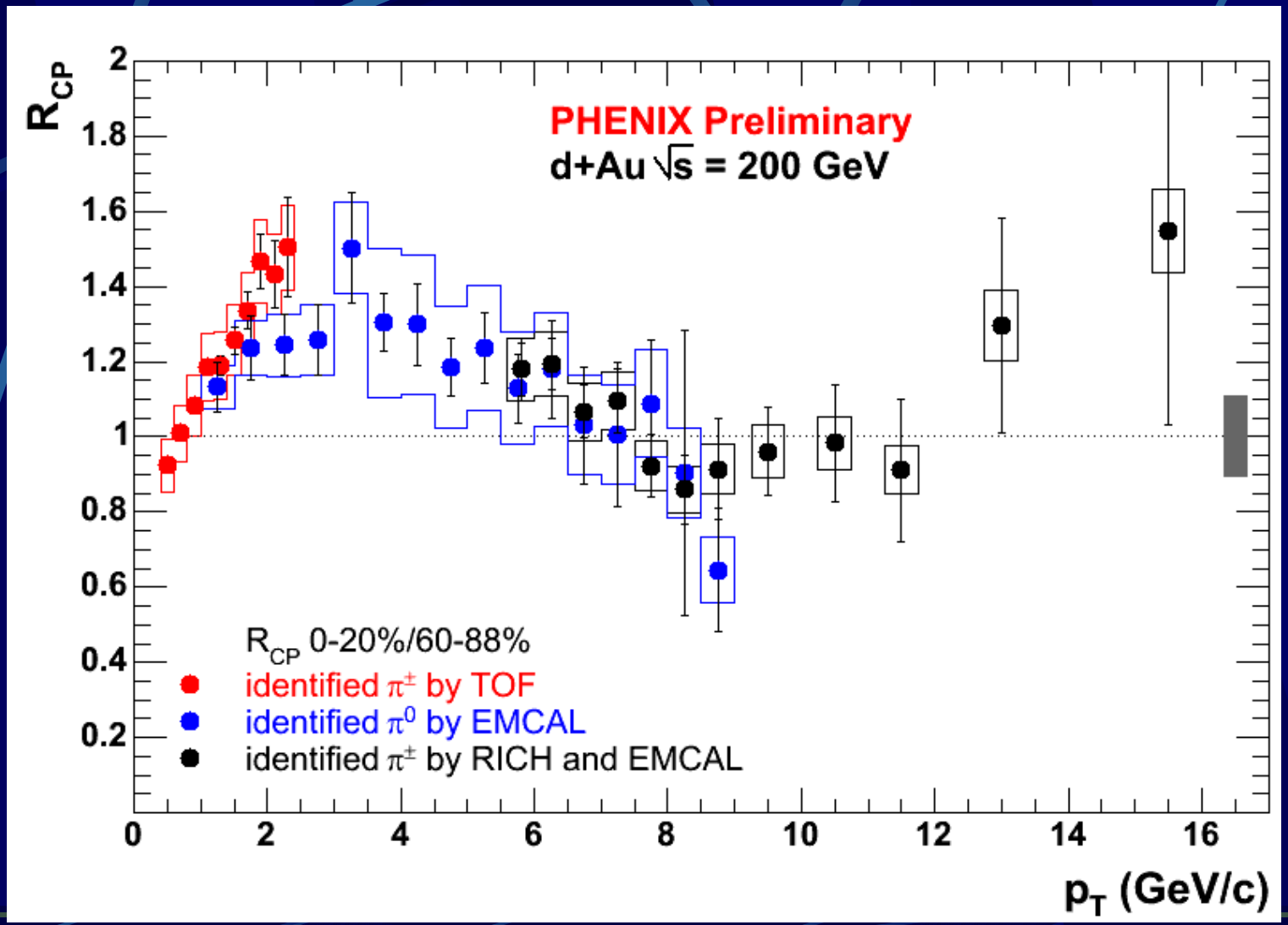
Cronin effect does not depend on quark flavor

- Does Cronin enhancement depend on strangeness content ? Compare p and Λ.



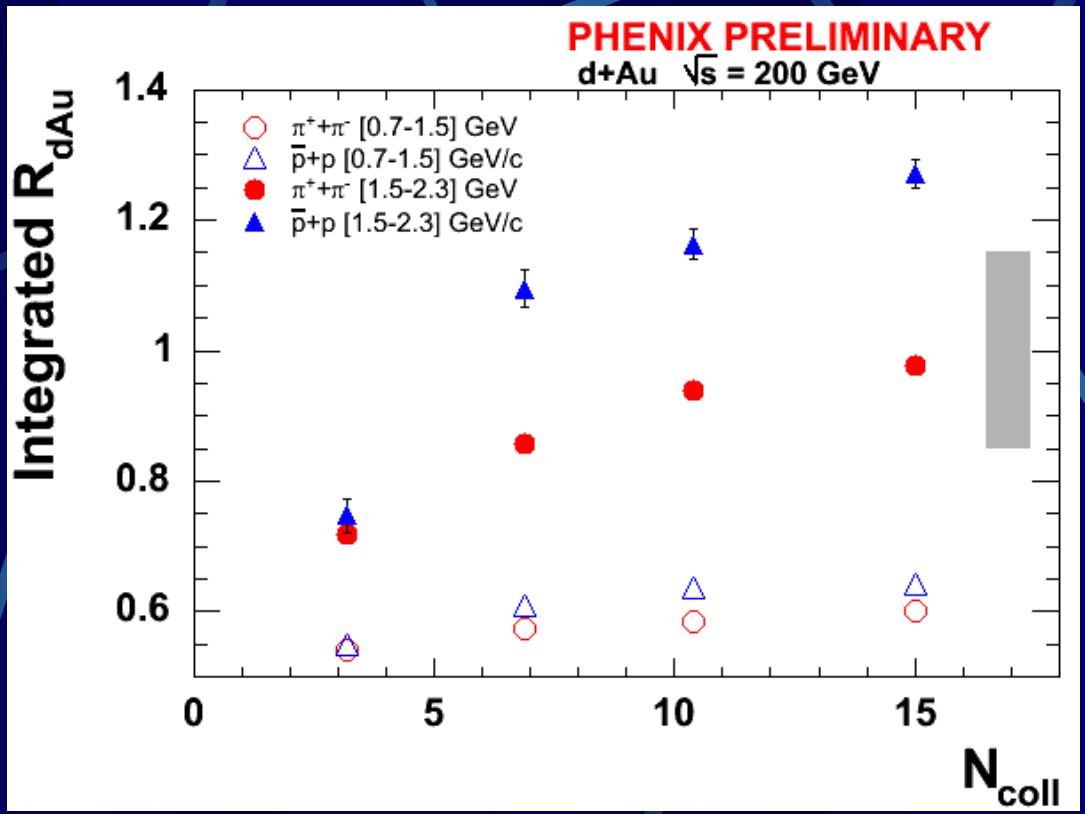
A. Taranenko

Cronin effect is limited to p_T <8 GeV/c



J.Jia

Enhancement tends to saturate with N_{coll}

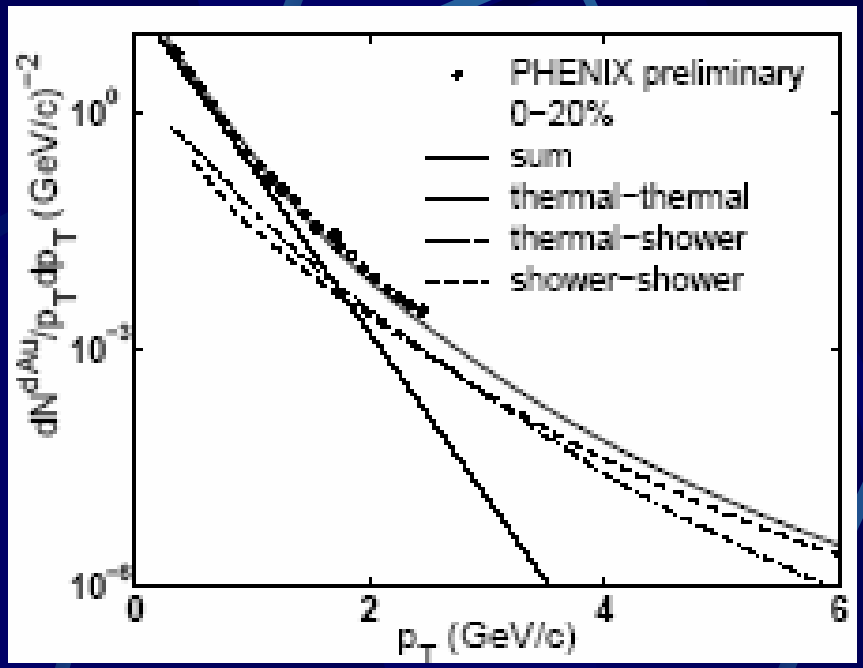


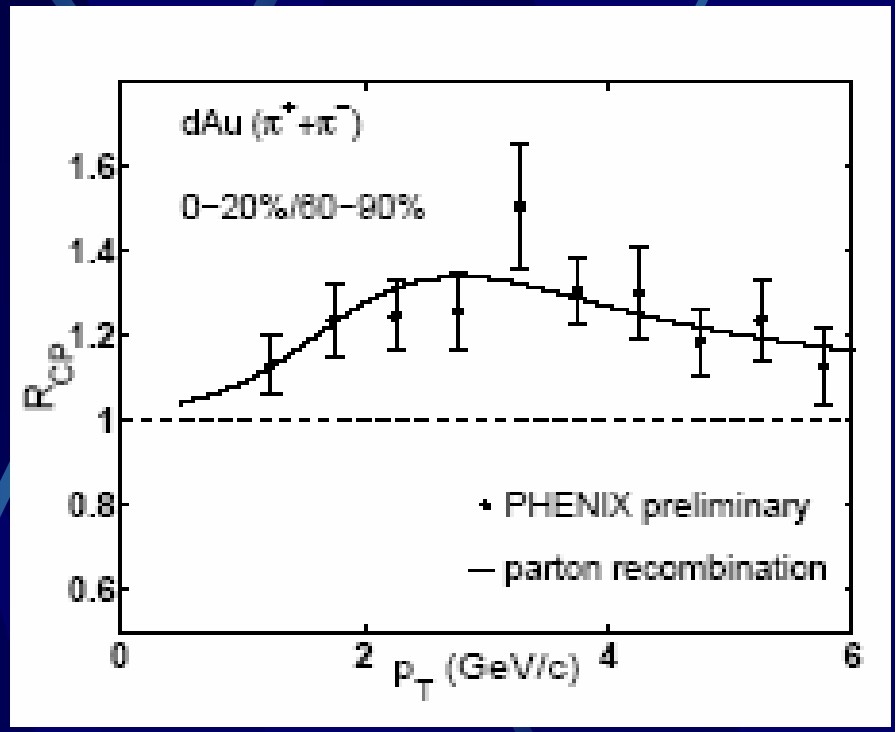
Felix Mathatias

- Similar centrality dependence for all particle species
- Enhancement grows with Ncoll and tends to saturate: additional scatterings do not contribute more broadening

Recombination as the source of Cronin effect ?

Hwa & Yang nucl-th:0403001





Paradigm shift: Cronin enhancement due to recombination

Final state effect

Attempt to explain AuAu and dAu with the same mechanism.

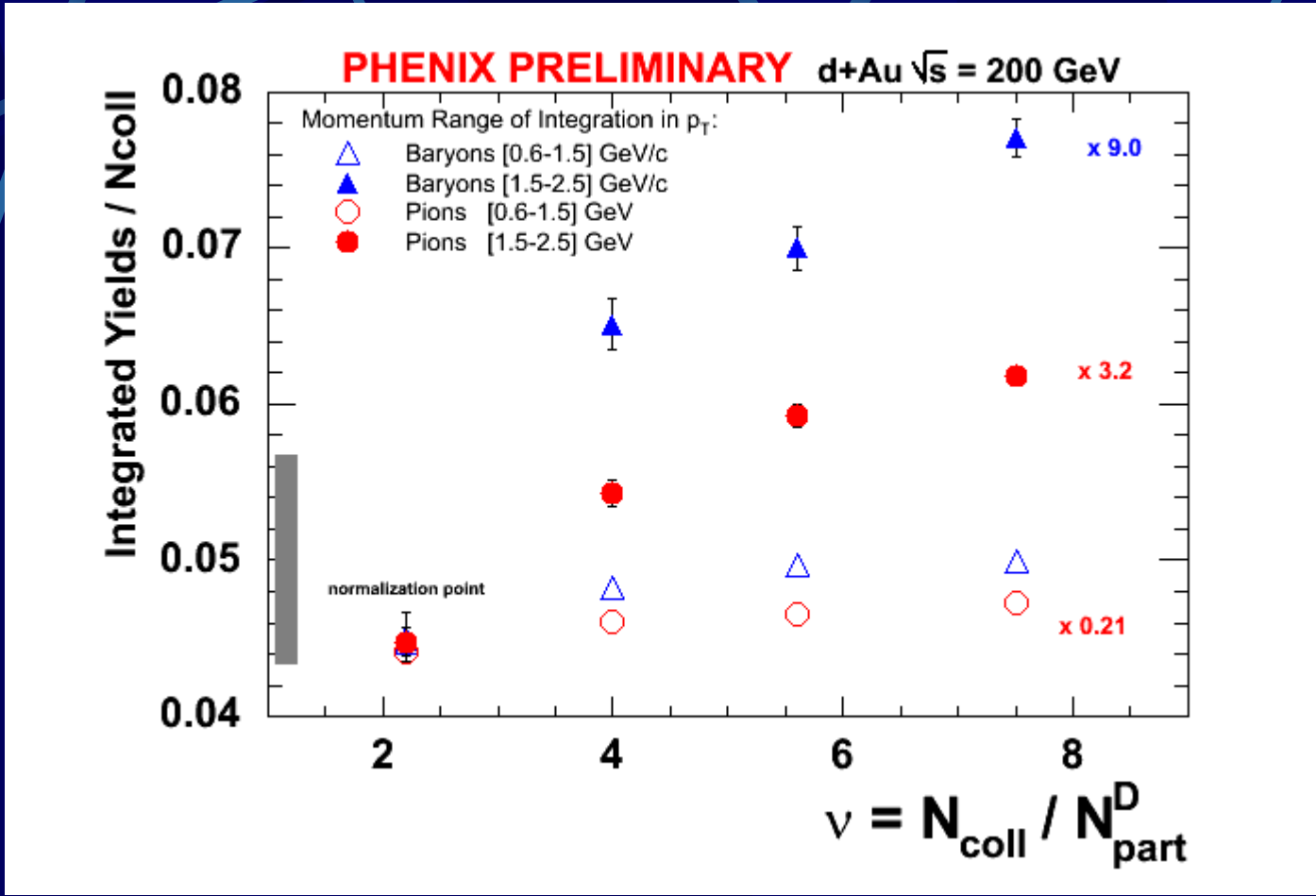
Need to compare to the baryon data !

Conclusions

- What do we learn from scaling of hadron yields in Au+Au collisions ?
  - Jet quenching at high p_T
  - Intermediate p_T shows pronounced baryon/meson differences
  - Recombination: success and challenges
    - Hadron yields and elliptic flow scale with the number of quarks: Points to partonic degrees of freedom
    - baryons show jettiness – need shower partons
- d+Au collisions:
  - jet quenching is confirmed as effect of the medium in AuAu collisions
  - Survey of experimental results for Cronin effect at RHIC energy
  - Baryons and mesons: do we need a paradigm shift to explain the difference ?

EXTRA

Cronin effect Yield/collision vs N_{coll}/N^{d}_{part}



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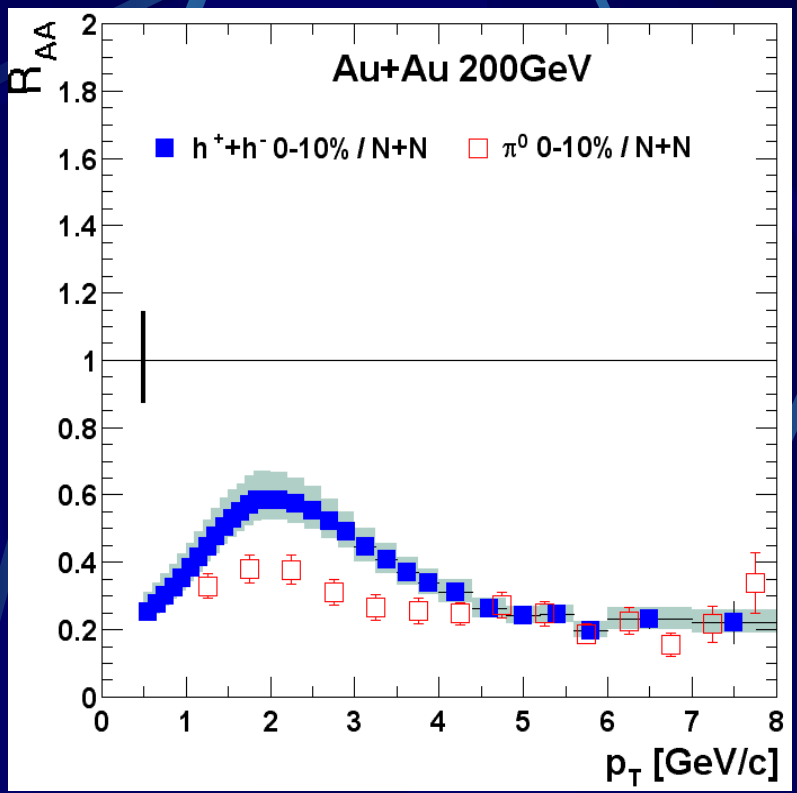
R_{AA} for π^0 and charged hadron

$$R_{AA} = \frac{\text{Yield}_{AuAu} / \langle N_{binary} \rangle_{AuAu}}{\text{Yield}_{pp}}$$



PHENIX AuAu 200 GeV
π^0 data: PRL 91 072301 (2003), nucl-ex/0304022.
charged hadron (preliminary) : NPA715, 769c (2003).